resulting from the inherent glass dispersion. Currently, most of the terrestrial network in the US and the world is based on standard fiber.

With DSF, waveguide dispersion is used to shift the zero dispersion wavelength to longer wavelengths. A conventional DSF has a zero dispersion wavelength at 1550 nm, coinciding with the minimum loss in a fused silica fiber. However, the zero dispersion wavelength can be shifted around by varying the amount of waveguide dispersion added. DSF is used exclusively in two countries, Japan and Italy, as well as in new long-haul links.

The limiting factors for a fiber-optic transmission line include loss, dispersion and gain equalization. Loss refers to the fact that the signal attenuates as it travels in a fiber due to intrinsic scattering, absorption and other extrinsic effects such as defects. Optical amplifiers can be used to compensate for the loss. Dispersion means that different frequencies of light travel at different speeds, and it comes from both the material properties and waveguiding effects. When using multi-wavelength systems, due to the non-uniformity of the gain with frequency, gain equalization is required to even out the gain over the different wavelength channels.

The typical solution to overcoming these limitations is to periodically place in a transmission system elements to compensate for each of these problems. For example, a dispersion compensator can be used to cancel the dispersion, an optical amplifier used to balance the loss and a gain equalization element used to flatten the gain. Examples of dispersion compensators include chirped fiber gratings and dispersion compensating fiber (DCF). Examples of optical amplifiers include erbium-doped fiber amplifiers (EDFAs), Raman amplifiers, and non-linear fiber amplifiers (NLFAs).

Another problem that arises in WDM systems is interaction or cross-talk between channels through non-linearities in the fiber. In particular, four-wave mixing (4WM) causes exchange of energy between different wavelength channels, but 4WM only phase matches near the zero dispersion wavelength. Consequently, if a fiber link is made from conventional DSF, it is difficult to operate a WDM system from around 1540-1560nm. This turns out to be quite unfortunate because typical EDFA's have gain from 1535-1565nm, and the more uniform gain band is near 1540-1560nm. A second fiber nonlinearity that can be troublesome is modulation instability (MI), which is 4WM where the fiber's nonlinear index-of-refraction helps to phase match. However, MI only phase matches when the dispersion is positive or in the so-called soliton regime. Therefore, MI can be avoided by operating at wavelengths shorter than the zero dispersion wavelength.

As the bandwidth utilization over individual fibers increases, the number of bands used for transmission increases. For WDM systems using a number of bands, additional complexities arise due to interaction between and amplification in multi-band scenarios. In particular, particular system designs are needed for Raman amplification in multi-band transmission systems. First, a new nonlinearity penalty arises from the gain tilt from the Raman effect between channels. This arises because long wavelength channels tend to rob energy from the short wavelength channels. Therefore, a means of minimizing the gain tilt on existing channels with the addition of new WDM channels is required.

To minimize both the effects of 4WM and Raman gain tilt, another technical strategy is to use distributed Raman amplification. In a WDM system with multi-bands, a complexity arises from interaction between the different pumps along the transmission line.

There is a need for multi-stage optical amplifiers and systems that have a distributed Raman amplification stage with bi-directional pumping. There is a further need for multi-stage optical amplifiers and systems that have dispersion compensation over a broad bandwidth.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide improved multi-stage optical amplifiers and systems.

Another object of the present invention is to provide multi-stage optical amplifiers and systems that have a distributed Raman amplification stage with bi-directional pumping.

Yet another object of the present invention is to provide multi-stage optical amplifiers and systems that have dispersion compensation over a broad bandwidth.

These and other objects of the present invention are achieved in a multi-stage optical amplifier that includes at least a distributed Raman amplifier fiber and a discrete amplifier fiber. The amplifier is configured to be coupled to at least one signal source that produces a plurality of signal wavelengths $\lambda_{s;}$ and at least a first pump source that produces one or more pump beam wavelengths $\lambda_{p.}$ A signal input port is coupled to the amplifier. A signal output port is coupled to the amplifier. The distributed Raman and discrete amplifier fibers are positioned between the signal input port and the signal output port. A first pump input port is coupled to a first end of the distributed Raman amplifier fiber. A second pump input port is coupled to a second end of the distributed Raman amplifier fiber. The first end is located closer to the signal input port than the second end. A third pump input port is coupled to the discrete amplifier fiber.

In another embodiment of the present invention, a multi-stage optical amplifier includes an optical fiber with at least a distributed Raman

amplifier fiber and a discrete amplifier fiber. The optical fiber is configured to be coupled to at least one signal source that produces a plurality of signal wavelengths λ_s and at least two pump sources that produce one or more pump beam wavelengths λ_p. At least a portion of one of the distributed Raman amplifier fiber and the discrete amplifier fiber is a dispersion compensating fiber. A signal input port is coupled to the optical fiber. A first pump input port is positioned between the signal input port and the distributed Raman amplifier fiber. A second pump input port is provided. The distributed Raman amplifier fiber is positioned between the signal input port and the second pump input port. The discrete amplifier fiber is positioned between the second pump input port and signal output port. A third pump input port is configured to pump the discrete Raman amplifier fiber.

In another embodiment of the present invention, a multi-stage optical amplifier includes an optical fiber with at least a distributed Raman amplifier fiber and a discrete amplifier fiber. The amplifier is configured to be coupled to at least one signal source that produces a plurality of signal wavelengths $\lambda_{s;}$ and at least a first pump source that produces one or more pump beam wavelengths $\lambda_{p.}$ A signal input port is coupled to the optical fiber. A signal output port is coupled to the optical fiber. The distributed Raman and discrete amplifier fibers are positioned between the signal input port and the signal output port. A first pump input port is coupled to the distributed Raman amplifier fiber. A second pump input port is coupled to the discrete amplifier fiber. A dispersion compensating member is coupled to the optical fiber. The dispersion compensating member has an opposite sign of dispersion slope and an opposite sign of dispersion relative to at least a portion of the optical fiber.

In another embodiment of the present invention, a multi-stage optical amplifier includes an optical fiber with a first Raman amplifier fiber

and a second Raman amplifier fiber. The optical fiber is configured to be coupled to a signal source that produces a plurality of signal wavelengths λ_s and a pump source that produces one or more pump wavelengths λ_p. The one or more pump wavelengths λ_p are less than at least a portion of the plurality of signal wavelengths λ_s. A signal input port, a signal output port, a pump input port and a dispersion compensating member are coupled to the optical fiber. A pump shunt is coupled to the optical fiber. At least a portion of the one or more pump wavelengths λ_p is coupled between the first Raman amplifier fiber and the second Raman amplifier fiber.

In another embodiment of the present invention, a multi-stage optical amplifier system includes a plurality of transmitters that produce a plurality of signal wavelengths λ_s. A multi-stage optical amplifier is provided and includes at least a distributed Raman amplifier fiber and a discrete amplifier fiber. The multi-stage optical amplifier is coupled to the plurality of transmitters, and configured to be coupled to at least a first pump source that produces one or more pump beam wavelengths λ_p. A signal input port and a signal output port are coupled to the amplifier. The distributed Raman and discrete amplifier fibers are positioned between the signal input port and the signal output port. A first pump input port is coupled to a first end of the distributed Raman amplifier fiber. A second pump input port is coupled to a second end of the distributed Raman amplifier fiber. The first end is located closer to the signal input port than the second end. A third pump input port is coupled to the discrete amplifier fiber. A plurality of receivers are coupled to the multi-stage optical amplifier.

In another embodiment of the present invention, a multi-stage optical amplifier system includes a plurality of transmitters that produce a plurality of signal wavelengths λ_s, and a multi-stage optical amplifier. The multi-stage optical amplifier includes an optical fiber with at least a

distributed Raman amplifier fiber and a discrete amplifier fiber. The multi-stage optical amplifier is coupled to the plurality of transmitters and configured to be coupled to at least two pump sources that produce one or more pump beam wavelengths λ_p. At least a portion of one of the distributed Raman amplifier fiber and the discrete amplifier fiber is a dispersion compensating fiber. A signal input port is coupled to the optical fiber. A first pump input port is positioned between the signal input port and the distributed Raman amplifier fiber. The multi-stage optical amplifier also includes a second pump input port. The distributed Raman amplifier fiber is positioned between the signal input port and the second pump input port and the discrete amplifier fiber is positioned between the second pump input port and signal output port. A third pump input port is configured to pump the discrete Raman amplifier fiber. A plurality of receivers are coupled to the multi-stage optical amplifier.

In another embodiment of the present invention, a multi-stage optical amplifier system includes a plurality of transmitters that produce a plurality of signal wavelengths λ_s, and a multi-stage optical amplifier. The multi-stage optical amplifier has an optical fiber with at least a distributed Raman amplifier fiber and a discrete amplifier fiber. The multi-stage optical amplifier is coupled to the plurality of transmitters and configured to be coupled to at least a first pump source that produces one or more pump beam wavelengths λ_p. A signal input port is coupled to the optical fiber. A signal output port is coupled to the optical fiber. The distributed Raman and discrete amplifier fibers are positioned between the signal input port and the signal output port. A first pump input port is coupled to the distributed Raman amplifier fiber. A second pump input port is coupled to the discrete amplifier fiber. A dispersion compensating member is coupled to the optical fiber. The dispersion compensating member has an opposite sign of dispersion slope and an opposite sign of dispersion relative to at least a

portion of the optical fiber. A plurality of receivers are coupled to the multi-stage optical amplifier.

In another embodiment of the present invention, a multi-stage optical amplifier system includes a plurality of transmitters that produce a plurality of signal wavelengths λ_s, and a multi-stage optical amplifier. The multi-stage optical amplifier has an optical fiber with a first Raman amplifier fiber and a second Raman amplifier fiber. The multi-stage optical amplifier is coupled to the plurality of transmitters and configured to be coupled to a pump source that produces one or more pump wavelengths λ_p. The one or more pump wavelengths λ_p are less than at least a portion of the plurality of signal wavelengths λ_s. A signal input port, a signal output port, a pump input port, a dispersion compensating member and a pump shunt are coupled to the optical fiber. At least a portion of the one or more pump wavelengths λ_p is coupled between the first Raman amplifier fiber and the second Raman amplifier fiber. A plurality of receivers are coupled to the multi-stage optical amplifier.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of one embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt.

Figure 2 illustrates that the cutoff wavelength of the fiber used with the present invention should be shorter than the pump and signal wavelengths.

Figure 3 is a schematic diagram illustrating the inclusion of a dispersion compensating element, a gain equalization element and an add/drop multiplexer to the multi-stage optical amplifier of the present invention.

Figure 4 is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes two pump shunts.

Figure 5 is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt and four amplifier fibers.

Figure 6 is a schematic diagram of one embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt and two pump sources.

Figure 7 is a schematic diagram of one embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt and a circulator.

Figure 8(a) is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes two Raman amplifier fibers and two pump sources.

Figure 8(b) is a schematic diagram of an embodiment of the present invention with a discrete and a distributed amplifier; where distributed amplification is added with only counter-propagating Raman pumps.

Figure 8(c) is a schematic diagram of an embodiment of the present invention similar to Figure 8(b) in which mid-span access is not available but bi-directional pumping is allowed.

Figure 9 is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes three Raman amplifier fibers and three pump sources.

Figure 10 is a schematic diagram illustrating four pump sources whose outputs are combined using wavelength and polarization multiplexing.

Figure 11 is a schematic diagram illustrating eight pump sources whose outputs are combined using wavelength and polarization multiplexing.

Figure 12 is a schematic diagram illustrating that Brillouin threshold for a laser diode pump source can be minimized with the inclusion of a spectrum broadening device.

Figure 13(a) is a schematic view of an open loop configuration for a dispersion managing Raman amplifier (DMRA) of the present invention with a bi-directionally pumped gain fiber.

Figure 13(b) is a schematic view of an open loop configuration for a DMRA of the present invention with the gain fiber split in two parts and counter-propagation of the pump and signal

Figure 13(c) is a schematic view of an open loop configuration for a DMRA of the present invention with other elements, such as gain equalization filters or optical add/drop multiplexers that are placed between two gain fibers.

Figure 13(d) is a schematic view of an open loop configuration for a DMRA of the present invention that is a two-stage amplifier, where the pump is inserted counter-propagating into the first stage and then after exiting the first stage is inserted counter-propagating into the second stage of the amplifier.

Figure 13(e) is a schematic view of an open loop configuration for a DMRA of the present invention that is similar to the Figure 13(d) embodiment but with one or more additional mid-stage elements such as an optical add/drop multiplexer.

Figure 13(f) is a schematic view of an open loop configuration for a DMRA of the present invention that is similar to the Figure 13(e) embodiment but with bi-directional pumping in the second stage to boost

the power gain without severe degradation in noise figure for the composite amplifier

Figure 14(a) is a schematic diagram of a hybrid system embodiment of the present invention with discrete amplifiers and distributed amplifiers that are configured for counter-propagating pumping and mid-span access.

Figure 14(b) is a schematic diagram of a hybrid system embodiment of the present invention with discrete amplifiers and distributed amplifiers configured for bi-directional pumping but not mid-span access.

Figure 14(c) is a schematic diagram of a hybrid system embodiment of the present invention with discrete amplifiers and distributed amplifiers configured for bi-directional pumping and mid-span access.

Figure 14(d) is a schematic diagram of a hybrid system embodiment of the present invention with discrete amplifiers and distributed amplifiers that are configured for counter-propagating pumping and no mid-span access.

Figure 15(a) is a schematic diagram of an embodiment of the present invention with distributed Raman amplifiers that are configured for counter-propagating pumping and mid-span access.

Figure 15(b) is a schematic diagram of an embodiment of the present invention with distributed Raman amplifiers that are configured for bi-directional pumping and no mid-span access.

Figure 15(c) is a schematic diagram of an embodiment of the present invention with distributed Raman amplifiers that are configured for bi-directional pumping and mid-span access.

Figure 15(d) is a schematic diagram of an embodiment of the present invention with distributed Raman amplifiers that are configured for counter-propagating pumping and no mid-span access. Figure 16 is a schematic diagram of a broadband booster amplifier embodiment of the present invention.

Figure 17 is a schematic diagram of a broadband pre-amplifier embodiment of the present invention.

Figure 18 is a schematic diagram of one embodiment of a broadband communication system of the present invention.

Figure 19 is a schematic diagram of another embodiment of a broadband communication system of the present invention.

Figure 20 is a schematic diagram of another embodiment of a broadband communication system of the present invention.

Figure 21 is a schematic diagram of another embodiment of a broadband communication system of the present invention.

Figure 22 is a schematic diagram of another embodiment of a broadband communication system of the present invention.

Figure 23(a) is a schematic diagram of a multi-stage optical amplifier embodiment of the present invention with at least a distributed Raman amplifier fiber and a discrete amplifier fiber.

Figure 23(b) is a schematic diagram of a multi-stage optical amplifier embodiment of the present invention that includes a second discrete Raman amplifier.

Figure 23(c) is a schematic diagram of a multi-stage optical amplifier embodiment system of the present invention.

Figure 24(a) is a schematic diagram of a multi-stage optical amplifier embodiment of the present invention that includes an optical fiber with a distributed Raman amplifier fiber and a discrete amplifier fiber.

Figure 24(b) illustrates a system that includes the Figure 24(a) multi-

stage optical amplifier.

Figure 25(a) is a schematic diagram of a multi-stage optical amplifier embodiment of the present invention with that is configured to be coupled to at least one signal source and at least one pump source 318.

Figure 25(b) is a schematic diagram of the Figure 25(a) multi-stage optical amplifier with a second discrete Raman amplifier fiber.

Figure 25(c) is a schematic diagram of a system that includes the Figure 25(a) multi-stage optical amplifier.

Figure 26(a) illustrates another embodiment of a multi-stage optical amplifier of the present invention that includes a dispersion compensating member and a pump shunt.

Figure 26(b), illustrates another embodiment of a multi-stage optical amplifier of the present invention with at least a portion of a pump shunt positioned between a distributed Raman amplifier and a signal input port.

Figure 26(c) is a schematic diagram of a system that includes the Figure 26(a) multi-stage optical amplifier.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

One embodiment of the present invention, as illustrated in Figure 1, is a multi-stage optical amplifier 10 with an optical fiber 12 including a first amplifier fiber 14 and a second amplifier fiber 16. Optical fiber 12 is configured to be coupled to a signal source 18 that produces at least a signal wavelength λ_s and a pump source 20 that produces a pump wavelength λ_p. Pump wavelength λ_p is less than signal wavelength λ_s. Signal input port 22, signal output port 24 and pump input port 26 are each coupled to optical fiber 12. A first lossy member 28 is coupled to optical fiber 12 and positioned between the first and second amplifier fibers 14 and 16 respectively. A pump shunt 30 is coupled to signal input port 22 and signal output port 24. Optionally, a second lossy member 32

is coupled to pump shunt 30. Pump shunt 30 can be an optical fiber that is integral with optical fiber 12 or a separate optical fiber.

Pump beam λ_p propagates towards signal input port 22 from first amplifier fiber 14 and away from signal input port 22 to second amplifier fiber 16.

First and second amplifier fibers 14 and 16 each preferably have a length greater than or equal to 200 m. Pump wavelength λ_p is preferably in the range of 1300 nm to 1530 nm, and the signal wavelength can be in the range of 1430 to 1530 nm. Suitable pump sources 20 include but are not limited to laser diodes (LD's), solid state lasers, fiber-based cascaded Raman wavelength shifters, cladding pumped fiber lasers and the like.

First lossy member 28 can be an optical isolator, an add/drop multiplexer. a gain equalization member, a dispersion compensation element and the like. One or both of first and second amplifier fibers 14 and 16 can be Raman amplifiers. Lossy elements 28 can also be placed before and after first and second amplifier fibers 14 and 16 to prevent disturbance of amplifier performance from spurious reflections from the transmission line. Additionally, a second lossy element 32 can be inserted into pump shunt 30 to reduce the multi-path interference of the signal beam in amplifiers 12 and 14.

Additionally, one or both of first and second amplifier fibers 14 and 16 can be implemented in dispersion compensating fiber (DCF). A DCF is a fiber whose zero dispersion point is shifted to wavelengths much longer than 1500 nm using the waveguide dispersion property. Consequently, DCF tend to have a small affective core area and significant germanium doping in the core, both of which lead to an enhancement of the Raman gain coefficient. DCF's are generally added periodically to a high-speed transmission link to compensate for the dispersion accumulated

in the line.

In one embodiment, multi-stage optical amplifier 10 operates in a violet band between 1430 and 1530 nm. Fiber 12 is a DSF with at least one fiber non-linearity effect and a zero dispersion wavelength. In this embodiment, multi-stage optical amplifier 10 provides gain in the violet band sufficiently far from the zero dispersion wavelength to avoid non-linearity effects.

First amplifier fiber 14 preferably has lower noise than second amplifier fiber 16. Second amplifier fiber 16 has a higher gain than first amplifier fiber 14. In one embodiment, first amplifier fiber 14 has an optical noise figure of less than 8 dB, and second amplifier fiber 16 has a gain level of at least 5 dB.

One or more WDM couplers 34 are used to couple a pump path from the signal input port 22 to the signal output port 24. WDM couplers 34 are designed to pass (couple over) the signal band while coupling over (passing) the pump beams. Exemplary WDM couplers 34 include fused-tapered fiber couplers, Mach-Zehnder couplers, thin-film dielectric filters, bulk diachronic elements and the like.

Signal input port 22 inputs signal λ_s which is amplified through Raman scattering when first and second amplifier fibers 14 and 16 are Raman amplifiers. The dispersion and length of the first and second amplifier fibers 14 and 16 can be selected to be of the same magnitude of dispersion-length product as the transmission link but of the opposite sign of dispersion. First and second amplifier fibers 14 and 16 are preferably made single spatial mode for pump source 20 and signal wavelengths by making the cut-off wavelength of the gain fiber shorter than the pump wavelength. In particular, the cut-off wavelength is the wavelength below which first and second amplifier fibers 14 and 16 support more than one

mode or becomes multi-mode. If the pump or signal falls into the multi-mode region, then additional noise arising from the beating between different modes may arise.

As shown in Figure 2 the fiber cut-off wavelength should be shorter than the pump wavelength λ_p. Pump wavelength λ_p is shorter than signal wavelength λ_s. Multi-stage optical amplifier 10 is pumped so the net gain equals or exceeds the sum of losses in the transmission link and first and second amplifier fibers 14 and 16.

Figure 3 illustrates that a dispersion compensating element 33, gain equalization element 29 or an add/drop multiplexer 31 can be included and positioned between first and second amplifier fibers 14 and 16.

Figure 4 illustrates an embodiment of multi-stage optical amplifier 10 with a third amplifier fiber 42. Second lossy member 32 is positioned between second and third amplifier fibers 16 and 42. A second pump shunt 44 is coupled to second and third WDM couplers 46 and 48. Additional amplifier fibers can also be included.

As illustrated in Figure 5, multi-stage optical amplifier 10 can include a third and a fourth amplifier fiber 42 and 50, respectively. In this embodiment, third and fourth amplifier fibers 42 and 50 are coupled to pump shunt 30. Second lossy member 32 is positioned between third and fourth amplifier fibers 42 and 50.

In another embodiment of multi-stage optical amplifier 10, multiple pump sources are utilized. In Figure 6, pump source 20 is positioned between first amplifier fiber 14 and first lossy member 28. A second pump source 52 is positioned between second amplifier fiber 16 and signal output port 24 and is coupled to a second pump input port 54. First pump source 20 produces a pump beam of wavelength λ_{p1} and second pump source 52 produces 52 a pump beam of wavelength λ_{p2}. Wavelength λ_{p1}

and wavelength λ_{p2} can be the same or different. Pump sources 20 and 52 collectively produce a pump beam of wavelength λ_p. Pump wavelength λ_p is less than a signal wavelength λ_s.

In another embodiment, illustrated in Figure 7, multi-stage amplifier 10 includes one or more circulators 56 to provide isolation between the first and second amplifier fibers 14 and 16. Circulator 56 also is useful as a means of dumping the remaining pump which can be reused elsewhere for monitoring purposes.

As illustrated in Figure 8(a), multi-stage optical amplifier 10 can have an open loop configuration, In this embodiment, optical fiber 12 is pumped by a pump beam generated by pump sources 20 and 52 and first and second amplifier fibers 14 and 16 are each Raman amplifiers. Optical fiber 12 is preferably single spatial mode at both the signal and pump wavelengths. Again, wavelength λ_{p1} and wavelength λ_{p2} can be the same or different. The pump beam has a wavelength shorter than the signal wavelengths. Pump sources 20 and 52 collectively produce a pump beam of wavelength λ_p. An amplified signal is then output through signal output port 24. Pump sources 20 and 52 are coupled in through WDM couplers 34 and 58 which transmit signal wavelength λ_s but couple over the pump wavelength λ_p . First lossy member 28 is positioned between pump input port 26 and signal output port 24. In this embodiment, the signal flows in a first direction and the pump beam flows in a reverse direction relative to the first direction. First and second amplifier fibers 14 and 16 are pumped in a counter-propagating manner. It may also be desirous to have bi-directional pumping in second amplifier fiber 16 to increase the power amplifier gain without severely impacting the noise figure of multi-stage optical amplifier 10. Other elements, including but not limited dispersion compensating element 33, gain equalization element and add/drop

multiplexer 31 may be included and positioned between first and second amplifier fibers 14 and 16.

In another embodiment, illustrated in Figures 8(b)-8(c), first amplifier fiber 14 is a distributed Raman amplifier fiber and second amplifier fiber 16 is a discrete Raman amplifier fiber. A distributed Raman amplifier fiber is an amplifier where at least some part of the transmission link is pumped and involved in amplification. In this embodiment, first lossy member 28 is not positioned between first and second amplifier fibers 14 and 16. In Figure 8(b) distributed amplification is added with only counter-propagating Raman pumps. When access at a mid-point stage exists alternate band pumps are added at different spatial points to minimize nonlinear interaction between pumps. In Figure 8(c) mid-span access is not available but bi-directional pumping is allowed. The embodiment of Figure 8(c) can be used where alternate band Raman pumps are launched in different directions in order to minimize interaction between pumps.

The open loop embodiment of multi-stage optical amplifier 10 can have three or more amplifier fibers. Referring now to Figure 9, an embodiment of multi-stage optical amplifier 10 is illustrated with third amplifier fiber 42 coupled to a third pump source 60 which is turn is coupled to a third pump input port 62. WDM coupler 64 is coupled to third pump input port 62. Some or all of first, second and third pump sources 20, 52 and 60 can be laser diode sources. Pump source 60 produces a pump beam of wavelength λ_{p3} . Wavelengths λ_{p1} , λ_{p2} and λ_{p3} can be the same or different. Pump sources 20, 52 and 60 collectively produce pump beam of wavelength λ_p. An amplified signal is then output through signal output port 24.

As illustrated in Figures 10 and 11 each of pump source 20,

52 and 60 can include multiple pump sources whose outputs can be combined using wavelength and polarization multiplexing. Multiple combination gratings 66 and PBS's 68 can be utilized. Additionally, some or all of the multiple pump sources which comprise pump sources 20, 52 and 60 can be laser diodes.Brillouin scattering is a relatively strong but low-bandwidth non-linear optical interaction occurring between counter-propagating pump and signal beams and involving acoustical phonons in a material the pump and signal propagate through. Brillouin scattering of pump energy in a Raman gain fiber is a potential problem with any low-bandwidth high-powered pump source. This problem can be particularly acute, however, for laser diode pump sources whose small cavity dimensions can lead to lasing on a small number of low-bandwidth modes. Significant Brillouin scattering can lead to serious Raman amplifier noise problems, especially for designs intended to be strictly counter-propagating.

Referring now to Figure 12, a spectrum broadening device 70 can be coupled to each pump source 20, 52 and 60. Spectrum broadening device 70 broadens the pump output spectrum and thus reduces Brillouin scattering. Suitable spectrum broadening devices 70 include but are not limited to, (i) a grating that is sufficiently broadband that can be chirped and cascade individual wavelengths, (ii) a grating positioned in a laser diode external cavity to cause appropriate line broadening, (iii) a laser diode pump driver that produces a dithering drive current, and (iv) a phase modulator driven by a broadband signal source. Additionally, pump pulsing can be used to broaden the spectrum.

For the purpose of the present invention, a DMRA is a Raman amplifier where the gain fiber is combined at least in part with a dispersion compensating element. The gain fiber can also serve the

purpose of at least partially balancing the dispersion of the transmission fiber. In one embodiment, the Raman amplifier can be implemented using at least a segment of dispersion compensating fiber, where the sign of dispersion of the DCF is opposite to that of at least a portion of the transmission fiber for at least a portion of the amplifier gain bandwidth.

In various embodiments of the present invention, dispersion mapping and/or dispersion compensating elements are inserted periodically in a transmission line to undo accumulated dispersion. In one specific embodiment, a DMRA is utilized and the periodicity of the dispersion compensation coincides with the periodicity of the amplifier spacing. For WDM systems, the accumulated dispersion returns to exactly zero for only one wavelength. This differing accumulated dispersion for the WDM channels results from the nonzero slope of the dispersion curve. This can be avoided if the dispersion compensating element has the opposite sign of dispersion slope (not just opposite sign of dispersion) from the transmission fiber. In another embodiment, the accumulated dispersion for the channels away from the balance wavelength can be compensated for with the opposite dispersion at the receiver.

Figure 13(a) illustrates an embodiment of the invention which uses an open-loop dispersion managing Raman amplifier design. The open-loop design is the simplest DMRA, although it may have a high pump power requirement. In the DMRA amplifier of Figure 13(a), an optical signal is input from an input port 72 to an optical amplifier fiber 74. Optical amplifier fiber 74 is pumped bi-directionally by light generated by pump sources 76 and 78. Optical amplifier fiber 74 preferably has only a single spatial mode at both the signal and pump wavelengths. The amplified signal is then output through an output port 80. Pump sources 76 and 78 are coupled in through wavelength-division multiplexers

(WDM's) 82 and 84, which transmit the signal wavelength but couple over the pump wavelength.

To avoid coupling any pumping light fluctuations to the amplified signal, it can be desirable to have a strictly counter-propagating pump and signal geometry. The open loop configuration of Figure 13(b) achieves this by splitting the amplifier fiber into first and second amplifier fibers 86 and 88. Pump sources 90 and 92 are used to pump first and second amplifier fibers 86 and 88, and WDM's 94 and 96 are used to couple the pump light into the amplifier fibers 86 and 88. In addition, an optical isolator 98 is placed between first and second amplifier fibers 86 and 88 to reduce double Rayleigh scattering in the amplifier and block the pump energy from pump source 92 that might otherwise enter amplifier fiber 86 through WDM 94.

Although Figure 13(b) uses isolator 98 between first and second amplifier fibers 86 and 88, it will be appreciated that other elements can be used, including but not limited to a gain equalization element, an optical add/drop multiplexer, and the like. These other elements, and isolator 98, can be utilized individually or in any combination. Figure 13(c) illustrates one embodiment of such a combination. Because of the typically high insertion loss associated with add/drop multiplexers, an effective isolation is achieved between first and second amplifier fibers 86 and 88 and thus an isolator is not used in this embodiment.

An alternate configuration for pumping the amplifier fiber is illustrated in Figure 13(d). In this embodiment, light from a pump source is introduced into first amplifier fiber 86, the pump beam is shunted around where the signal is introduced and extracted from the amplifier, and then the pump light enters second amplifier fiber 88. An optional WDM 99 may be used to remove any remaining pump energy to avoid

damage to isolator 98. Isolator 98 is placed between first and second amplifier fibers 86 and 88. This embodiment provides numerous advantages including but not limited to, first amplifier fiber 86 acts as a low-noise pre-amplifier that experiences high gain near a signal input port 100 due to its relative proximity to a pump input port 102. Isolator 98 in the signal path further reduces noise and multi-path interference (MPI) including double Rayleigh scattering, and second amplifier fiber 88 acts as a power amplifier that can deplete any remaining pump power without reducing the gain of the first amplifier fiber and thus the amplifier exhibits superior gain saturation performance

Additionally, at the mid-stage of the two-stage amplifier other elements such as add/drop multiplexers and the like, can also be placed. For example, Figure 13(e) illustrates the two-stage design of Figure 13(d) along with an optical add/drop multiplexer 104 at the mid-stage. Further, the embodiments illustrated in Figures 13(d) and Figure 13(e) are unique and advantageous even if dispersion compensation fiber is not used as the amplifier fiber. Furthermore, it may also be desirable to have bi-directional pumping in second amplifier fiber 88 in order to increase the power amplifier gain without severely impacting the noise figure of the composite amplifier. This is illustrated in Figure 13(f).

Figures 14(a) through 14(d) illustrate various hybrid systems of the present invention that include discrete and distributed amplifiers. Figure 14(a) illustrates one distributed amplification embodiment with only counter-propagating Raman pumps and having mid-span access. Different band pumps can be added at various spatial points to minimize nonlinear interaction between pumps. If mid-span access is not available and bi-directional pumping is allowed, then the Figure 14(b) embodiment can be used, where various band Raman pumps are launched in different

directions to minimize interaction between pumps. If bi-directional pumping is allowed and mid-span access is also available, a more uniform pumping can be achieved using the Figure 14(c) embodiment. Finally, if only counter-propagating pumps are allowed and there is no mid-span access, as in Figure 14(d), then the various pump bands can be launched orthogonally polarized. This arrangement takes advantage of the fact that the Raman gain for cross-polarized light is about one-tenth the strength of Raman gain for co-polarized light. It will be appreciated that polarization multiplexing can also be combined advantageously with any of the embodiments of Figures 14(a)-14(c).

In other embodiments of the present invention, illustrated in Figures 15(a) through 15(d) only distributed Raman gain is used. Figures 15(a)-15(d) illustrate corresponding pumping configurations to those of Figures 14(a)-14(d) but use only distributed Raman amplification. Figure 15(a) shows a purely counter-propagating pumping scheme where mid-span access exists. The different pump bands can be spatially dispersed. Figure 15(b) illustrates a bi-directionally pumped situation with no mid-span access, where different pumps are launched in different directions. In the Figure 15(c) embodiment, a combination of bi-directional pumping and mid-span access is utilized to make the gain more spatially uniform. Figure 15(d) illustrates the launch of one or more cross-polarized pump bands. The cross-polarized pumps of the Figure 15(d) embodiment can be advantageously combined with any of the embodiments illustrated in Figures 15(a)-15(c).

Multi-stage optical amplifier 10 can be an in-line broadband amplifier, a booster amplifier, a broadband pre-amplifier and incorporated in any variety of different broadband communication systems. In another embodiment, illustrated in Figure 16, the present invention is a broadband

booster amplifier 106 that includes a multi-stage optical amplifier 10 coupled to a transmitter 108. Transmitter 108 can include a WDM combiner 110 and a plurality of transmitters 112. The plurality of transmitters 112 transmit a plurality of wavelengths. The plurality of wavelengths may include at least a first band of wavelengths and a second band of wavelengths. With the present invention, a variety of different transmitters 112 can be utilized including but not limited to laser diodes, tunable lasers, or broadband sources such as continuum sources or light-emitting diodes.

Figure 17 illustrates a broadband pre-amplifier embodiment of the present invention. Broadband pre-amplifier 113 includes multi-stage optical amplifier 10 coupled to a receiver 114. Receiver 114 can include a WDM splitter 116 coupled to a plurality of receivers 118. Suitable receivers 118 include but are not limited to germanium or InGaAs or InGaAsP detectors followed by electronics well known to those skilled in the art.

In another embodiment, illustrated in Figure 18, the present invention is a broadband communication system 120. In this embodiment, multi-stage optical amplifier 10 is an in-line broadband amplifier. Multi-stage optical amplifier 10 is coupled to one or more transmitters 108 and one or more receivers 114.

Figure 19 illustrates another embodiment of the present invention which is a broadband communication system 122 that includes multi-stage optical amplifier 10 coupled to a broadband pre-amplifier 124. Multi-stage optical amplifier 10 is coupled to one or more transmitters 108 and broadband pre-amplifier 124 is coupled to one or more receivers 114.

Figure 20 illustrates yet another embodiment of a broadband communication system 126 with a broadband booster amplifier 128

coupled to multi-stage optical amplifier 10. One or more transmitters 108 are coupled to broadband booster amplifier 128. One or more receivers 114 are coupled to multi-stage optical amplifier 10.

Another embodiment of a broadband communication system 130 is illustrated in Figure 21. In this embodiment, an in-line amplifier 132 is coupled to receiver 114 and to a transmitter 134. Transmitter 134 includes multi-stage optical amplifier 10 coupled to transmitter 108.

Figure 22 illustrates another broadband communication system 136 of the present invention. Broadband communication system 136 includes multi-stage optical amplifier 10 coupled to broadband booster amplifier 128 and broadband pre-amplifier 124. Broadband booster amplifier 128 is coupled to one or more transmitters 108. Broadband pre-amplifier 124 is coupled to one or more receivers 114.

As illustrated in Figure 23(a), a multi-stage optical amplifier 200 has at least a distributed Raman amplifier fiber 210 and a discrete amplifier fiber 212. Amplifier 200 is configured to be coupled to at least one signal source 214 that produces a plurality of signal wavelengths $\lambda_{s;}$. At least a first pump source 216 produces one or more pump beam wavelengths $\lambda_{p.}$ A signal input port 218 is coupled to amplifier 200. A signal output port 220 is coupled to amplifier 200. Distributed Raman and discrete amplifier fibers 210 and 212 are positioned between signal input port 218 and signal output port 220. A first pump input port 222 is coupled to a first end 224 of distributed Raman amplifier fiber 210. A second pump input port 226 is coupled to a second end 228 of distributed Raman amplifier fiber 210. First end 224 is located closer to signal input port 218 than second end 228. A third pump input port 230 is coupled to discrete amplifier fiber 212.

First and second pump input ports 222 and 226 are configured to couple pump light into distributed Raman amplifier fiber 210. Second and third pump input ports 226 and 230 can be located at a first location and

first pump input port 222 is located at a second location that is distanced from the first location. The second location can be distanced in an amount of at least 20 km relative to the first location. Discrete amplifier fiber 212 can be a discrete Raman amplifier fiber.

First pump input port 222 is coupled to first pump source 216, and second pump input port 226 is coupled to a second pump source 231. In various embodiments, each of the first and second pump sources 216 and 231 can be a laser diode pump source. Distributed and discrete Raman amplifier fibers 210 and 212 can have lengths greater than or equal to 200 m. One or more pump beam wavelengths λ_p can be in the range of 1300 nm to 1530 nm.

Distributed Raman amplifier fiber 210 can have an effective optical noise figure that is less than an optical noise figure of the discrete amplifier fiber 212 for at least a portion of the plurality of signal wavelengths λ_S. Discrete amplifier fiber 212 can have a higher gain than distributed Raman amplifier fiber 210 for at least a portion of the plurality of signal wavelengths λ_S.

Distributed and discrete Raman amplifier fibers 210 and 212 can each be dispersion compensating fibers. Distributed Raman amplifier fiber 210 can have an effective optical noise figure of less than 8 dB for at least a portion of the plurality of signal wavelengths λ_S. Discrete amplifier fiber 212 can have a gain level of at least 5 dB for at least a portion of the plurality of signal wavelengths λ_S.

Referring now to Figure 23(b), multi-stage optical amplifier 200 can include a second discrete Raman amplifier fiber 232. A pump shunt 234 can also be coupled to the optical fiber. When pump shunt 234 is included, at least a portion of the one or more pump wavelengths λ_p is coupled between discrete Raman amplifier fiber 212 and second discrete Raman amplifier fiber 232. A first lossy member 236 can be positioned between

signal input port 218 and signal output port 220. First lossy member 236 can be lossy in at least one direction. First lossy member 236 can include an optical isolator, an add/drop multiplexer, a gain equalization member, a dispersion compensation member, a WDM coupler and the like or any combination of such elements.

In one embodiment, multi-stage optical amplifier 200 includes a transmission fiber 238. Additionally, multi-stage optical amplifier 200 can also include dispersion compensating fiber The dispersion compensating fiber can have an opposite sign of dispersion slope and an opposite sign of dispersion relative to at least a portion of: transmission fiber 238 plus any portions of the distributed, discrete, and second discrete Raman amplifier fibers 210, 212, and 232 that are not comprised of dispersion compensating fiber.

Multi-stage optical amplifier 200 can be included in a system, illustrated in Figure 23(c). In this embodiment, a plurality of transmitters 242 and a plurality of receivers 244 are coupled to multi-stage optical amplifier 200.

In another embodiment of the present invention, illustrated in Figure 24(a), a multi-stage optical amplifier 300 includes an optical fiber 310 with at least a distributed Raman amplifier fiber 312 and a discrete amplifier fiber 314. Optical fiber 310 is configured to be coupled to at least one signal source 316 that produces a plurality of signal wavelengths λ_s and at least two pump sources 318 and 320 that produce one or more pump beam wavelengths λ_p. At least a portion of one of distributed Raman amplifier fiber 312 and discrete amplifier fiber 314 is a dispersion compensating fiber 322. A signal input port 324 is coupled to optical fiber 310.

A first pump input port is 326 positioned between signal input port 324 and distributed Raman amplifier fiber 312. A second pump input port 328 is included. Distributed Raman amplifier fiber 312 is positioned

between signal input port 324 and second pump input port 328. Discrete amplifier fiber 314 is positioned between second pump input port 328 and signal output port 329. A third pump input port 330 is configured to pump discrete Raman amplifier fiber 314.

Dispersion compensating fiber 322 can have a zero dispersion point that is shifted to wavelengths greater than 1500 nm using the waveguide dispersion property. Dispersion compensating fiber 322 can have an opposite sign of dispersion slope and an opposite sign of dispersion relative to at least a portion of optical fiber 310. In one embodiment, dispersion compensating fiber 322 has an opposite sign of dispersion slope and an opposite sign of dispersion relative to a majority of optical fiber 310. In another embodiment, dispersion compensating fiber 322 has an opposite sign of dispersion slope and an opposite sign of dispersion relative to the cumulative dispersion of the entire non-dispersion compensating portion of optical fiber 310.

In one embodiment, discrete amplifier fiber 314 is a discrete Raman amplifier fiber. Distributed and discrete Raman amplifier fibers 312 and 314 can have lengths greater than or equal to 200 meters.

In one embodiment, the one or more pump beam wavelengths λ_p are in the range of 1300 nm to 1530 nm. Distributed Raman amplifier fiber 312 can have an effective optical noise figure of less than 8 dB for at least a portion of the plurality of signal wavelengths λ_S. Discrete amplifier fiber 314 can have a gain level of at least 5 dB for at least a portion of the plurality of signal wavelengths λ_S.

Multi-stage optical amplifier 300 can also include a first lossy member 332 that can be positioned between signal input port 324 and signal output port 329. First lossy member 332 is lossy in at least one direction.

Multi-stage optical amplifier 300 can be included in a system, illustrated in Figure 24(b). In this embodiment, a plurality of transmitters

334 and a plurality of receivers 336 are coupled to multi-stage optical amplifier 300.

Referring now to Figure 25(a), a multi-stage optical amplifier 400 includes an optical fiber 410 with at least a distributed Raman amplifier fiber 412 and a discrete amplifier fiber 414. Multi stage optical amplifier 400 is configured to be coupled to at least one signal source 416 that produces a plurality of signal wavelengths $\lambda_{s;}$ and at least a first pump source 418 that produces one or more pump beam wavelengths $\lambda_{p.}$ First pump source can be a laser diode pump source. The one or more pump beam wavelengths λ_p can be in the range of 1300 nm to 1530 nm.

A signal input port 420 is coupled to optical fiber 410. A signal output port 422 is coupled to optical fiber 410. Distributed Raman and discrete amplifier fibers 412 and 414 are positioned between signal input port 420 and signal output port 422. A first pump input port 424 is coupled to distributed Raman amplifier fiber 412. A second pump input port 426 is coupled to discrete amplifier fiber 414. A dispersion compensating member 428 is coupled to optical fiber 410. Dispersion compensating member 428 has an opposite sign of dispersion slope and an opposite sign of dispersion relative to at least a portion of optical fiber 410.

Dispersion compensating member 428 can be positioned between distributed Raman amplifier fiber 412 and discrete amplifier fiber 414. A portion of optical fiber 410 can be the dispersion compensating member 428. Additionally, at least a portion of optical fiber 410 can include a dispersion compensating fiber.

Dispersion compensating member 428 can have an opposite sign of dispersion slope and an opposite sign of dispersion relative to a majority of optical fiber 410. In another embodiment, dispersion compensating member 428 can have an opposite sign of dispersion slope and an opposite sign of dispersion relative to a cumulative dispersion of the entire optical fiber 410.

Discrete amplifier fiber 414 can be a discrete Raman amplifier fiber. Distributed and discrete Raman amplifier fibers 412 and 414 can have lengths greater than or equal to 200 meters. In one embodiment at least one of the distributed and discrete Raman amplifier fibers 412 and 414 is a dispersion compensating fiber.

As illustrated in Figure 25(b), optical fiber 410 can include a second discrete Raman amplifier fiber 430. Multi-stage optical amplifier 400 can include a third pump input port 432 that is coupled to second discrete Raman amplifier fiber 430. Multi-stage optical amplifier 400 can also include a first lossy member 434 positioned between signal input port 420 and the signal output port 422. First lossy member 434 is lossy in at least one direction.

Referring to Figure 25(c), multi-stage optical amplifier 400 can be included in a system. In this embodiment, a plurality of transmitters 436 and a plurality of receivers 438 are coupled to multi-stage optical amplifier 400.

Figure 26(a) illustrates another embodiment of a multi-stage optical amplifier 500 of the present invention. An optical fiber 510 includes first and second Raman amplifier fibers 512 and 514. Optical fiber 510 is configured to be coupled to a signal source 516 that produces a plurality of signal wavelengths λ_s and a pump source 518 that produces one or more pump wavelengths λ_p. The one or more pump wavelengths λ_p are less than at least a portion of the plurality of signal wavelengths λ_s. The one or more pump wavelengths λ_p can be in the range of 1300 to 1530 nm

A signal input port 520, signal output port 522 and a pump input port 524 are all coupled to optical fiber 510. A dispersion compensating member 526 and a pump shunt 528 are each coupled to optical fiber 510. At least a portion of the one or more pump wavelengths λ_p are coupled between the first Raman amplifier fiber 512 and the second Raman

amplifier fiber 514.

In one embodiment, optical fiber 510 includes a transmission fiber and dispersion compensating member 526 has an opposite sign of dispersion slope and an opposite sign of dispersion relative to at least a portion of optical fiber 510. In another embodiment, optical fiber 510 includes a transmission fiber and dispersion compensating member 526 has an opposite sign of dispersion slope and an opposite sign of dispersion relative to a majority of optical fiber 510. Dispersion compensating member 526 can also have an opposite sign of dispersion slope and an opposite sign of dispersion relative to a cumulative dispersion of the entire optical fiber 510.

Referring now to Figure 26(b), a pump shunt 528, which may be an optical fiber, can be coupled to signal input port 520 and signal output port 522. In one embodiment, a distributed Raman amplifier 530 is coupled to signal input port 520. At least a portion of pump shunt 528 can be positioned between distributed Raman amplifier 530 and the signal input port 520.

A first lossy member 532 can be coupled to optical fiber 510. In one embodiment, first lossy member 532 is coupled to pump shunt 528.

In one embodiment, at least a portion of the first and/or second Raman amplifier fibers 512 and 514 is a dispersion compensating fiber. The dispersion compensating fiber can have an opposite sign of dispersion slope and an opposite sign of dispersion relative to at least a portion of optical fiber 510 where the optical fiber 510 includes a transmission fiber.

Multi-stage optical amplifier 500 can also include at least one WDM coupler 534 to couple a pump path from signal input port 520 to signal output port 522. Pump source 518 can include at least one laser diode pump source 536 and can be coupled to pump input port 524.

As illustrated in Figure 26(c), multi-stage optical amplifier 500 can be included in a system. In this embodiment, a plurality of transmitters 536

and a plurality of receivers 538 are coupled to multi-stage optical amplifier 500.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention.

What is claimed is: